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(54) **CORRECTION OF FABRICATED SHAPES IN ADDITIVE MANUFACTURING**

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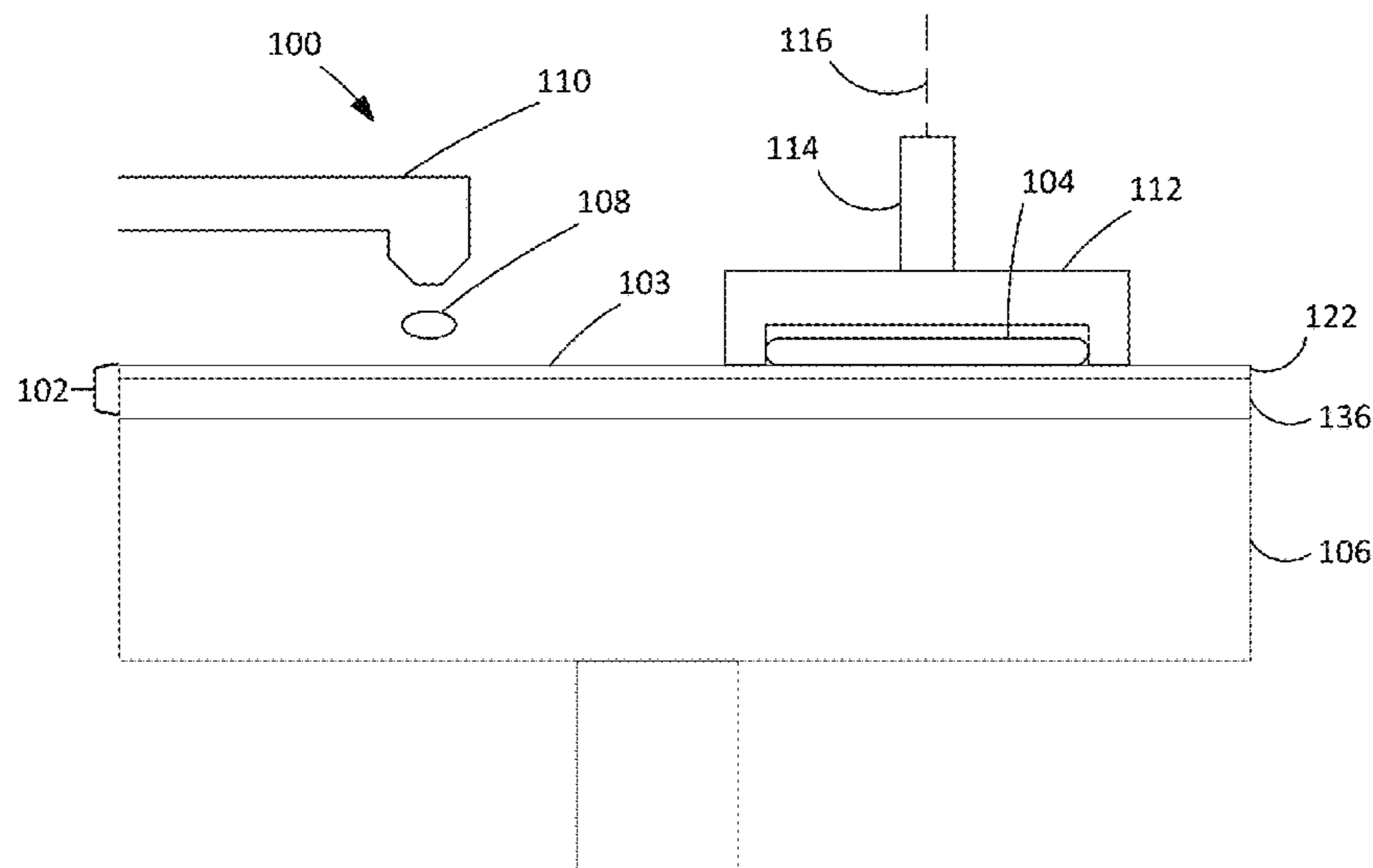
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(57) **ABSTRACT**

A method of fabricating an object using an additive manufacturing system includes receiving data indicative of a desired shape of the object to be fabricated by droplet ejection. The desired shape defines a profile including a top surface and one or more recesses. Data indicative of a pattern of dispensing feed material is generated to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and a plurality of layers of the feed material are dispensed by droplet ejection in accordance to the pattern.

20 Claims, 10 Drawing Sheets



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B33Y 50/02 (2015.01)
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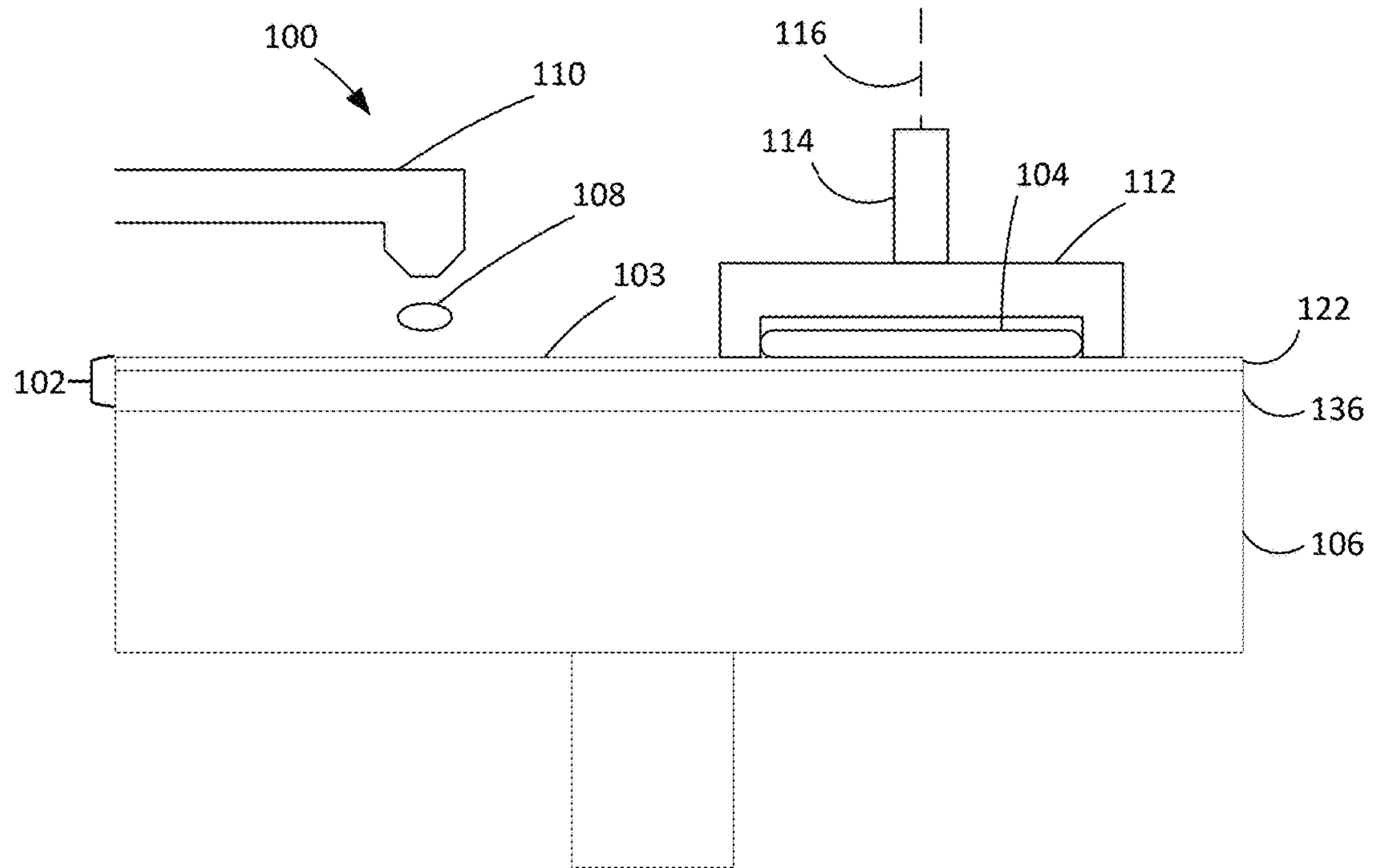


FIG. 1

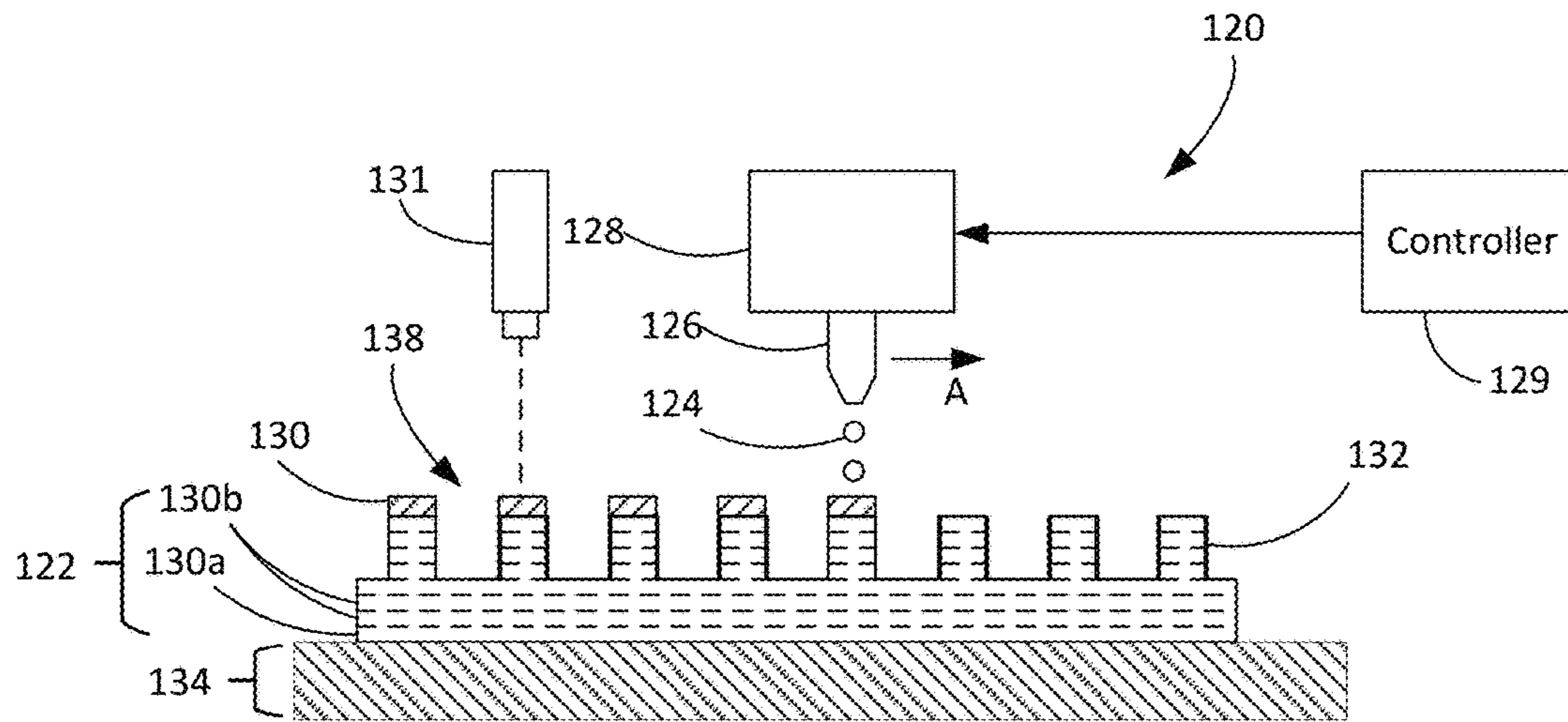


FIG. 2

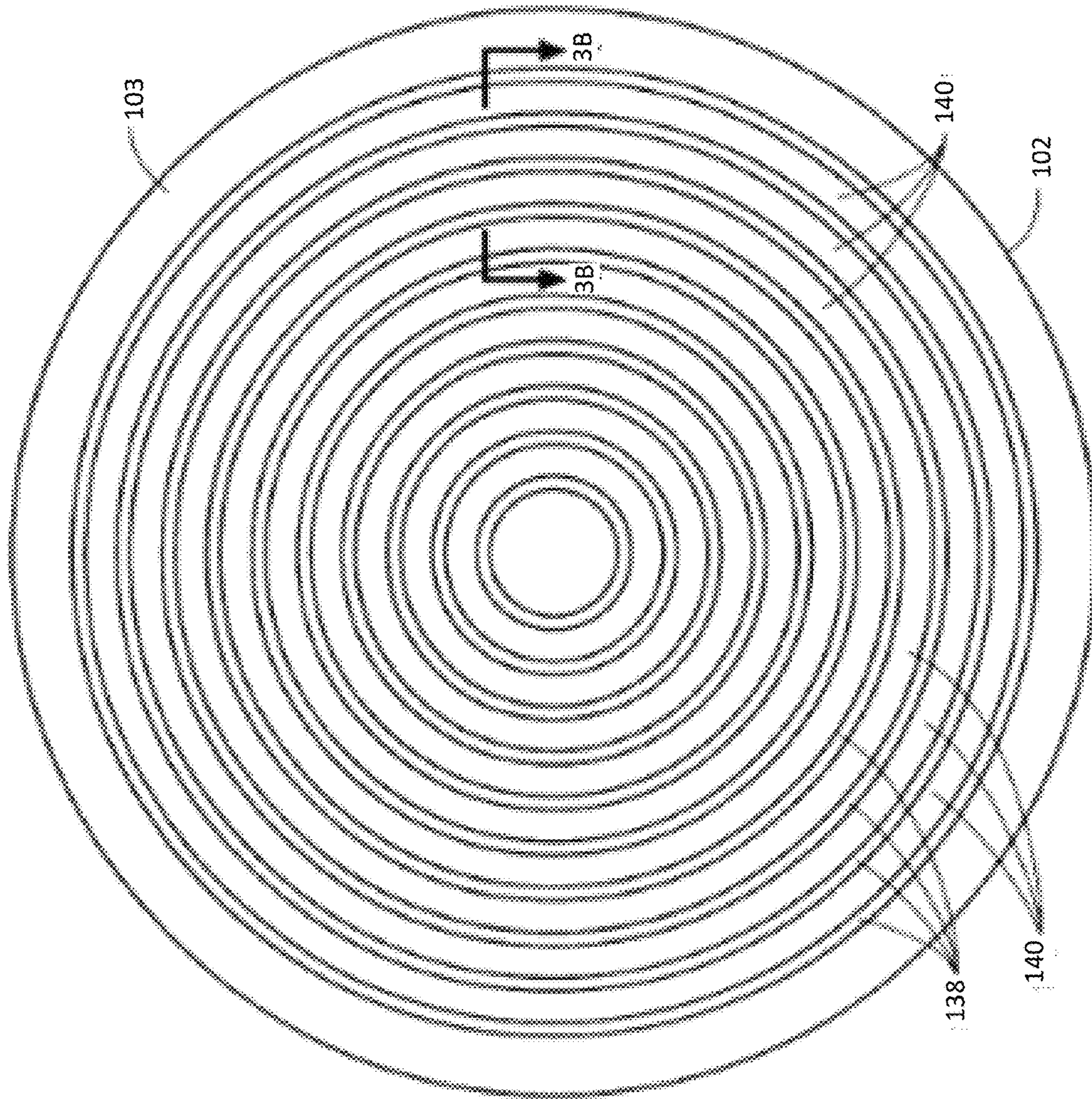


FIG. 3A

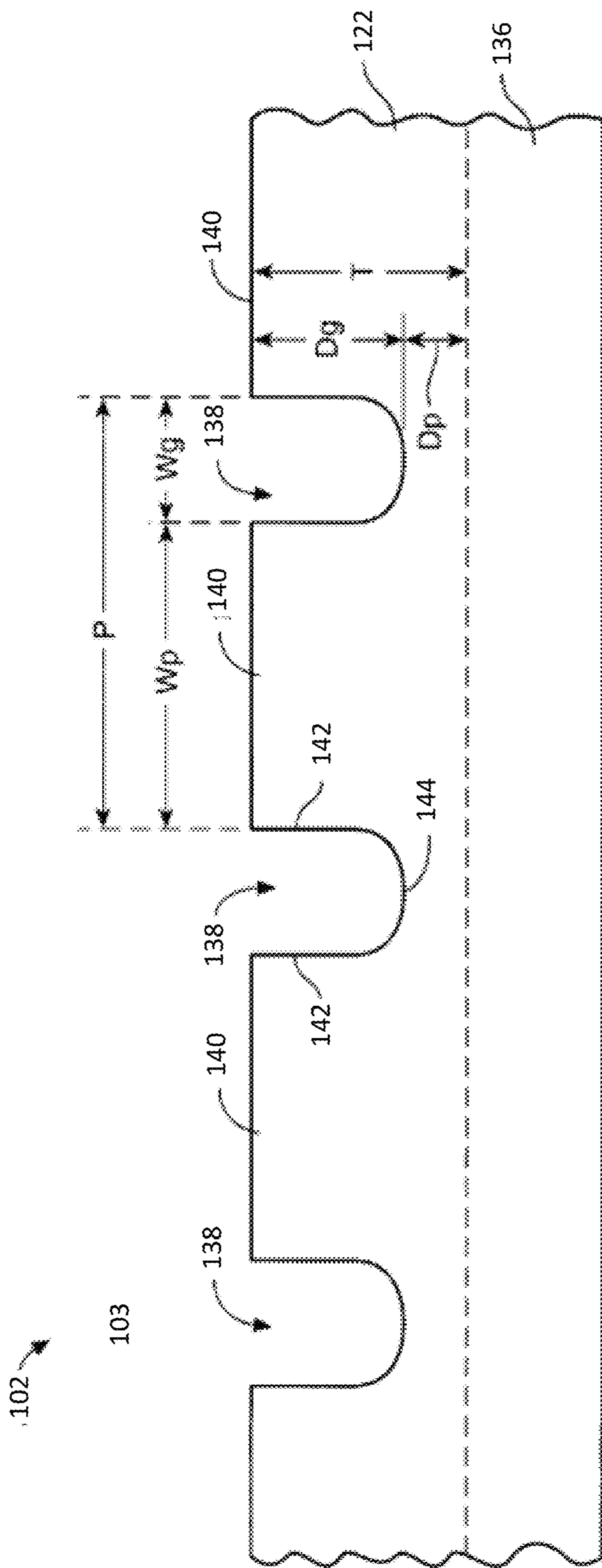


FIG. 3B

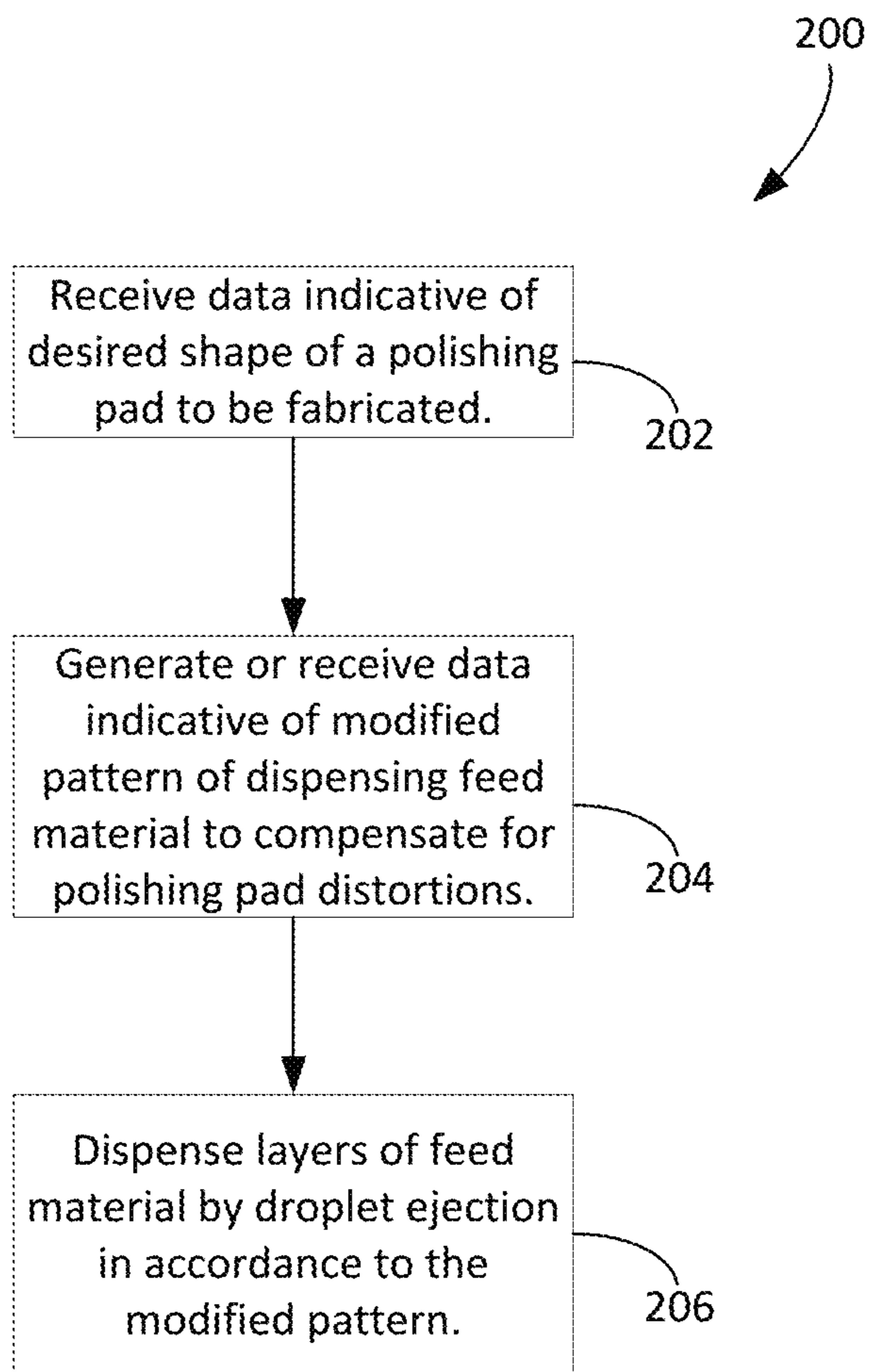


FIG. 4

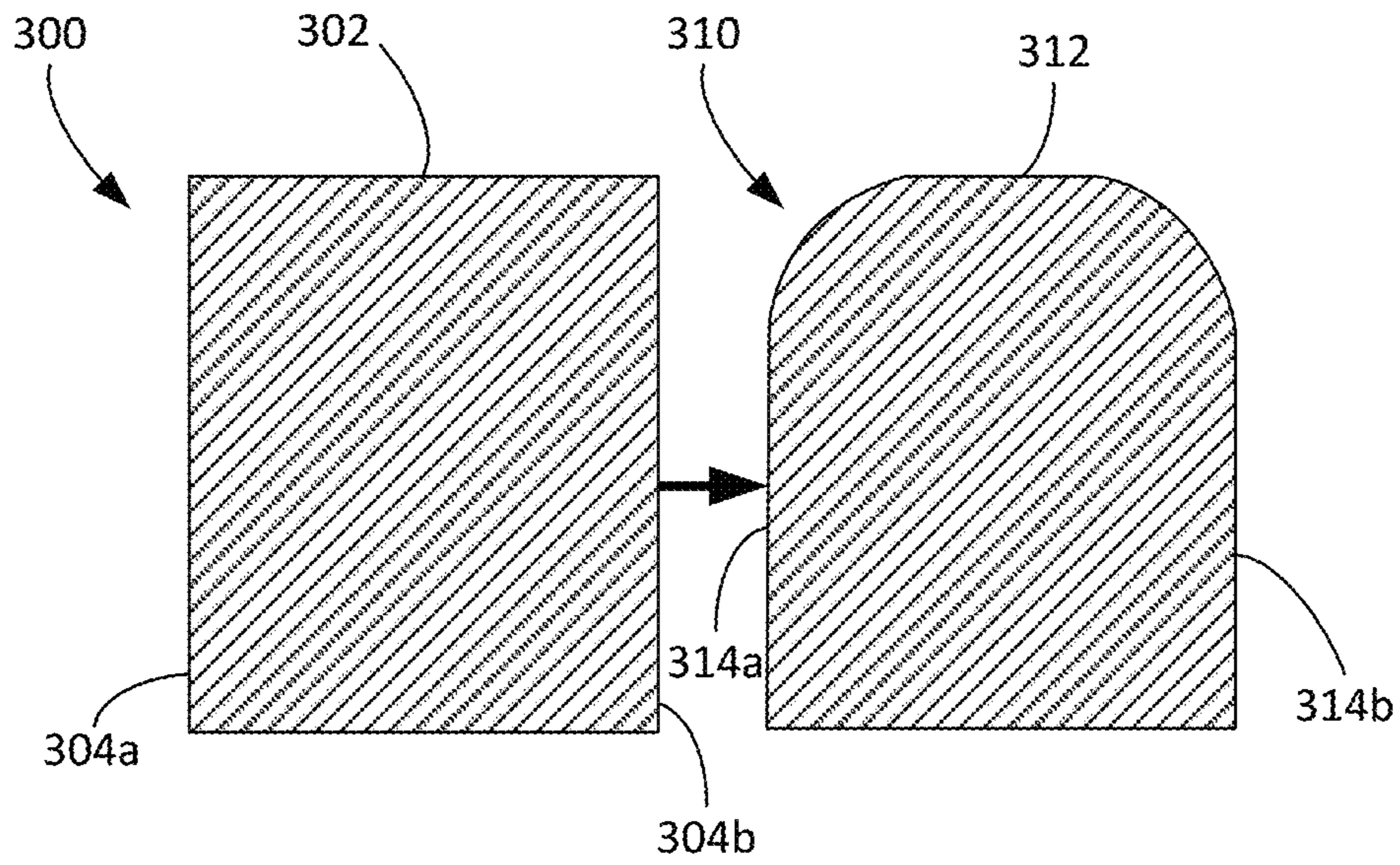


FIG. 5

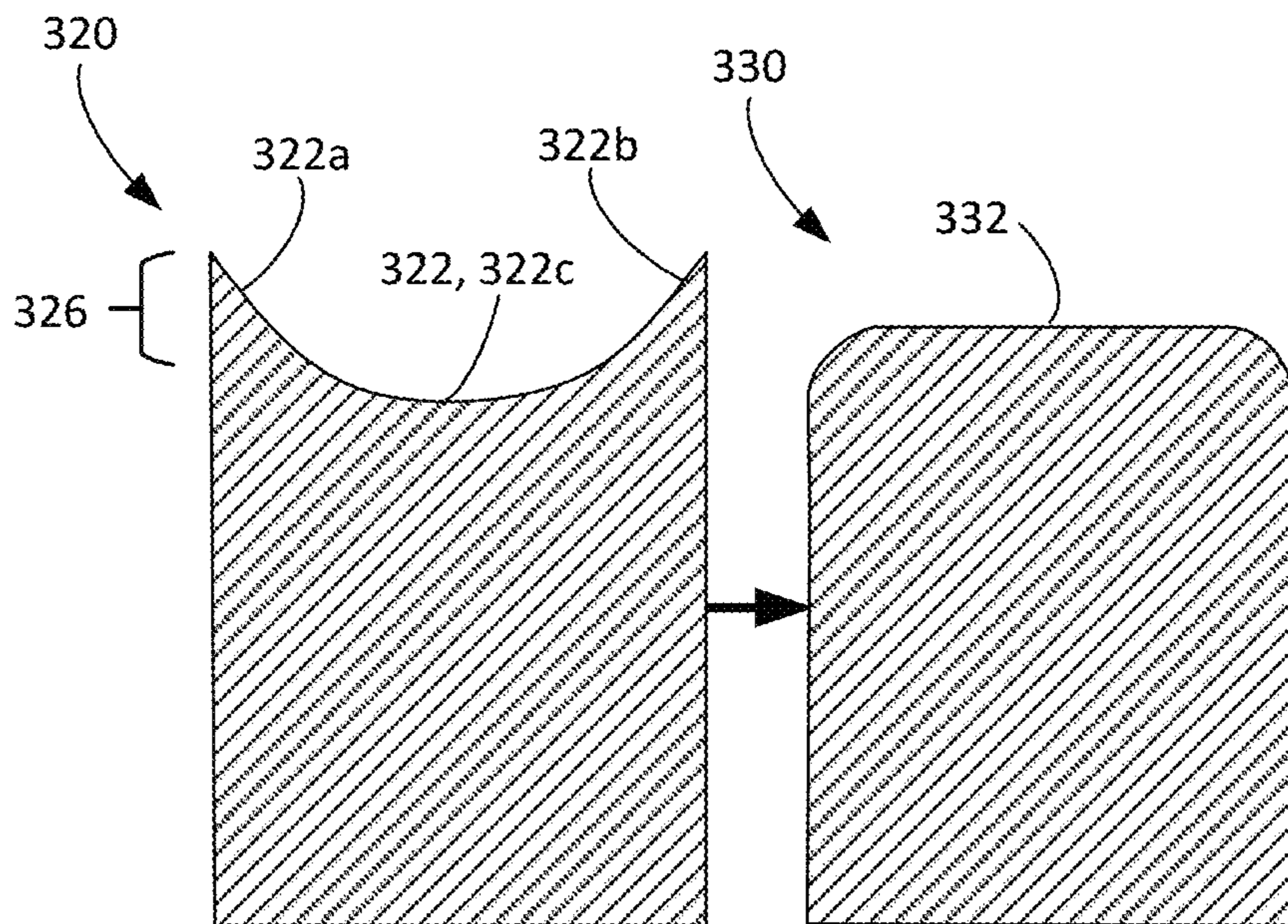


FIG. 6

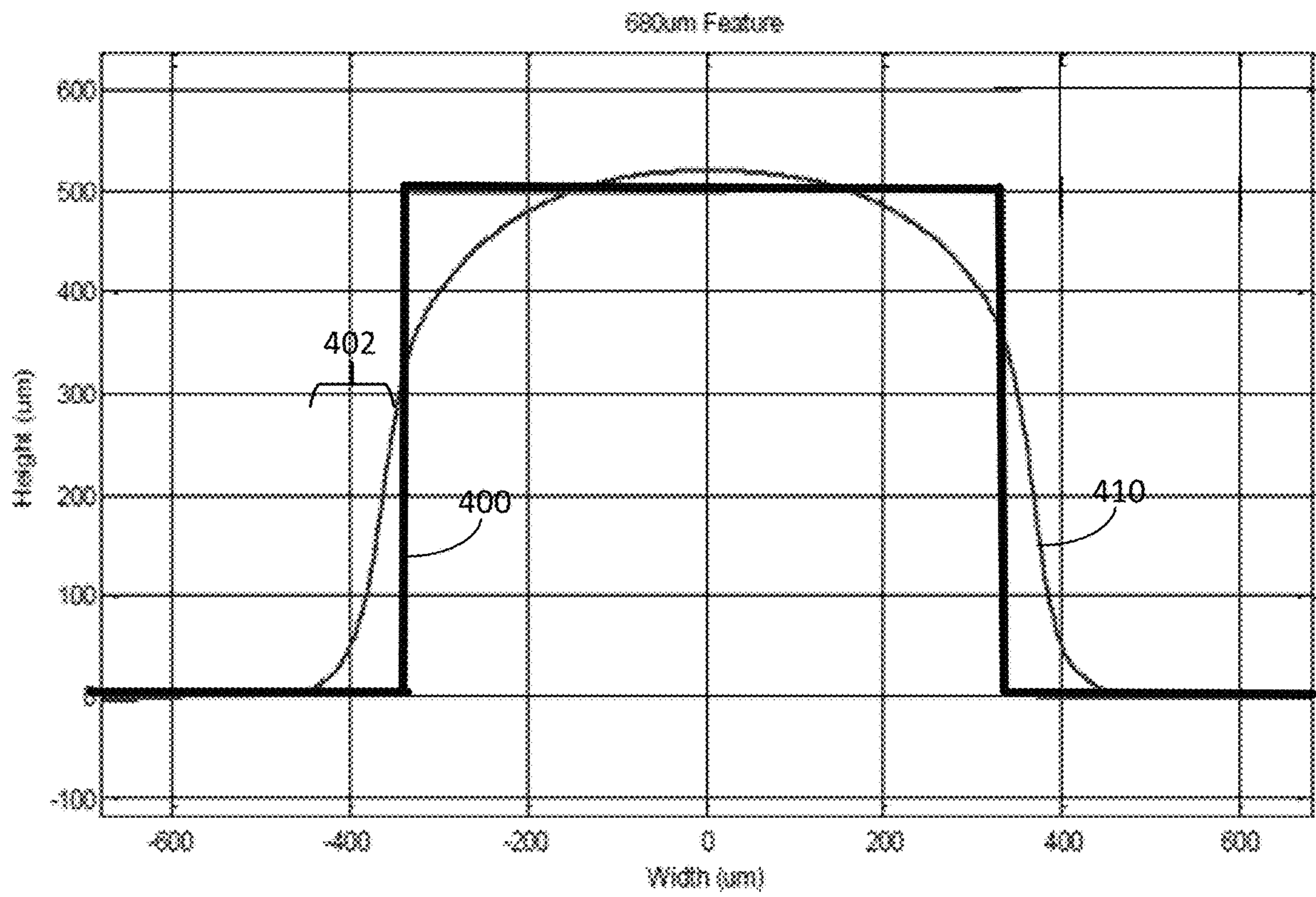


FIG. 7

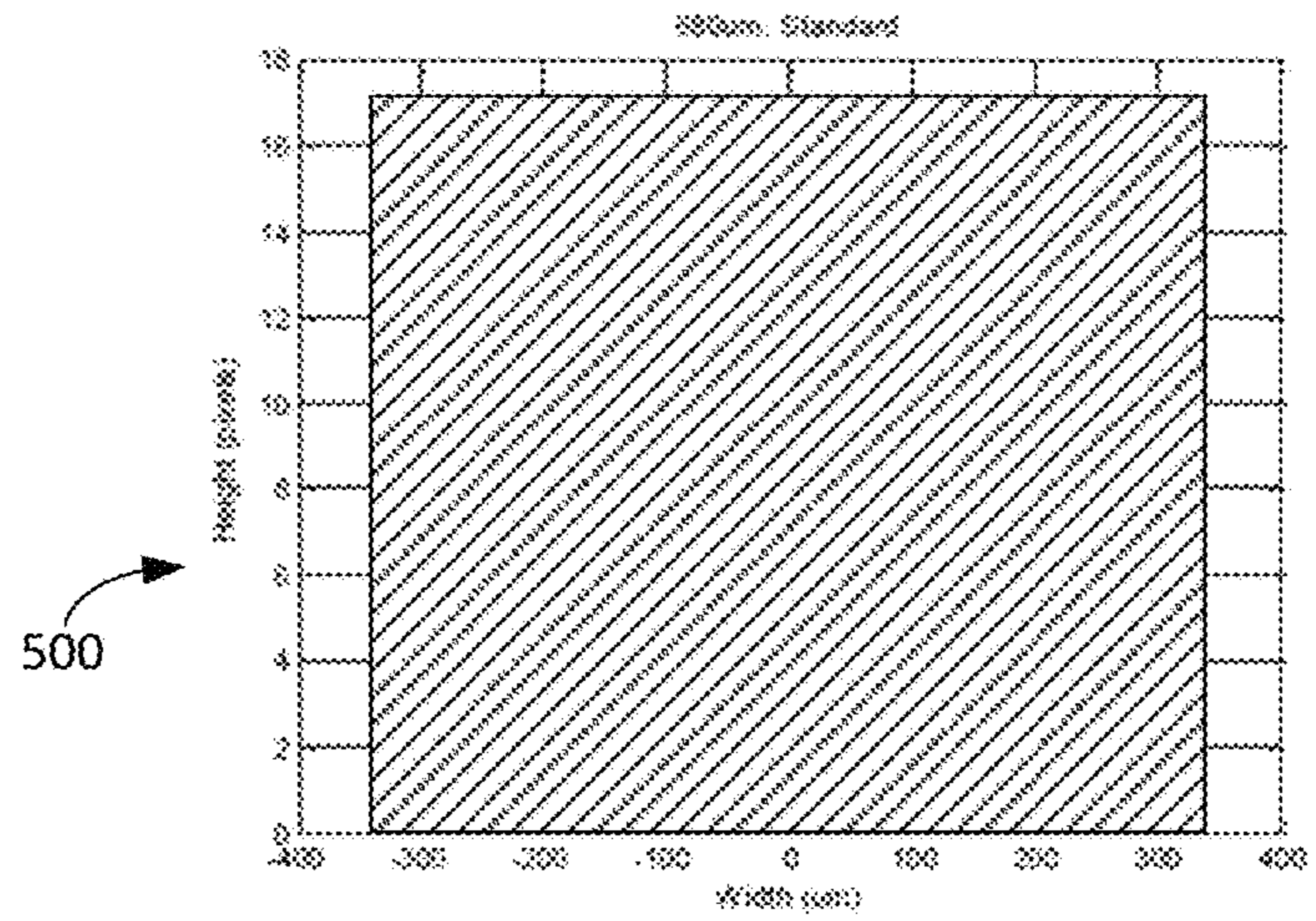


FIG. 8A

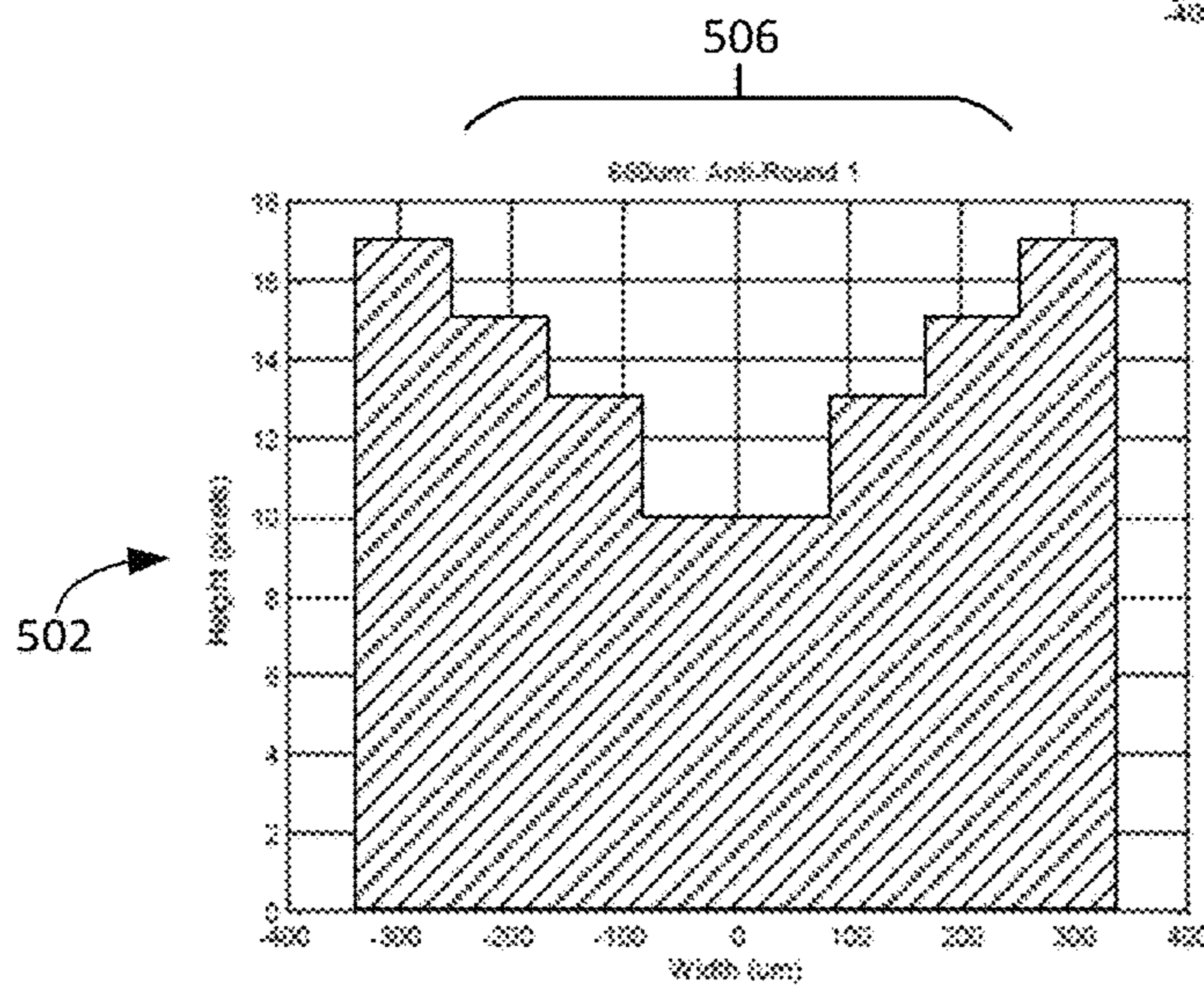


FIG. 8B

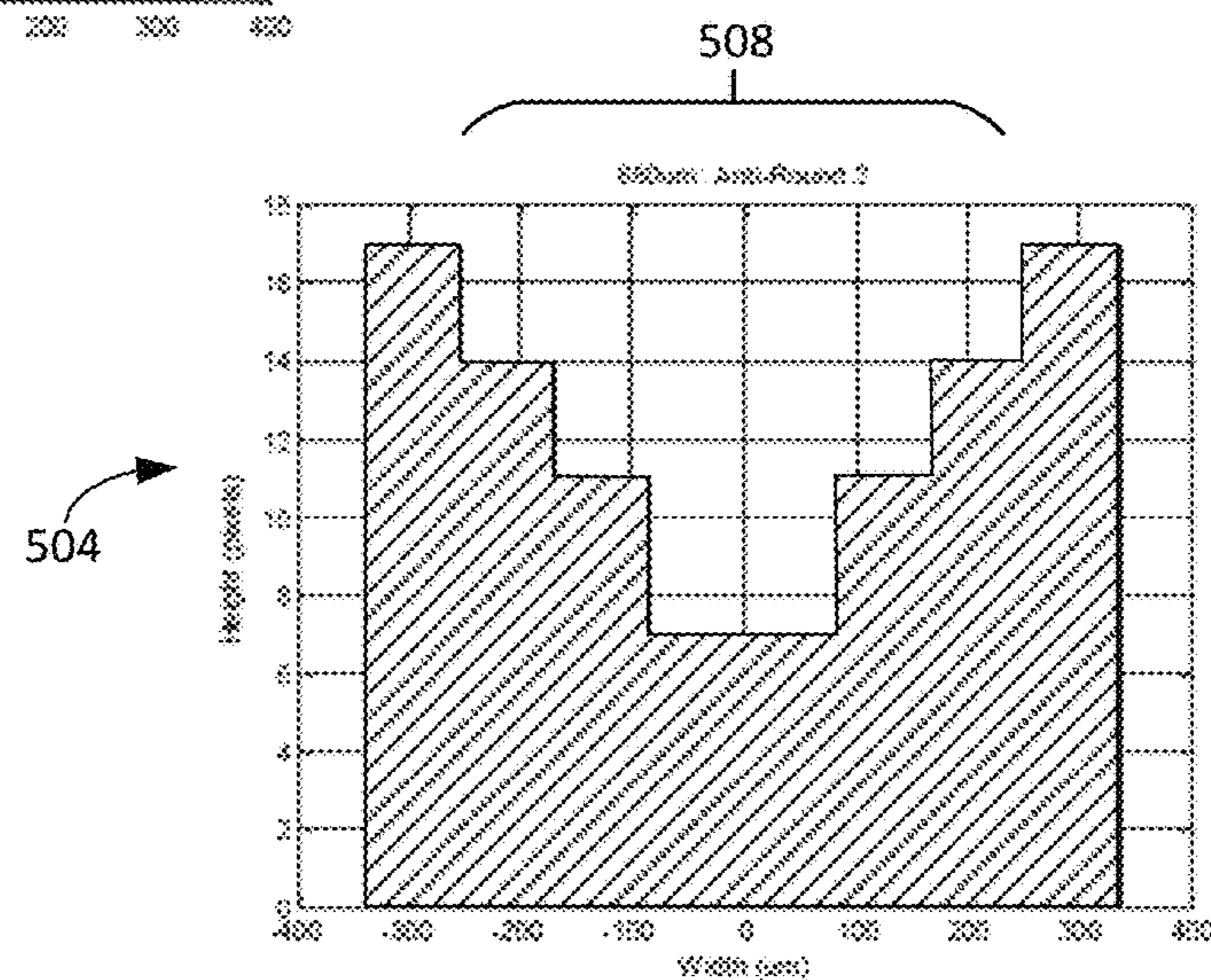


FIG. 8C

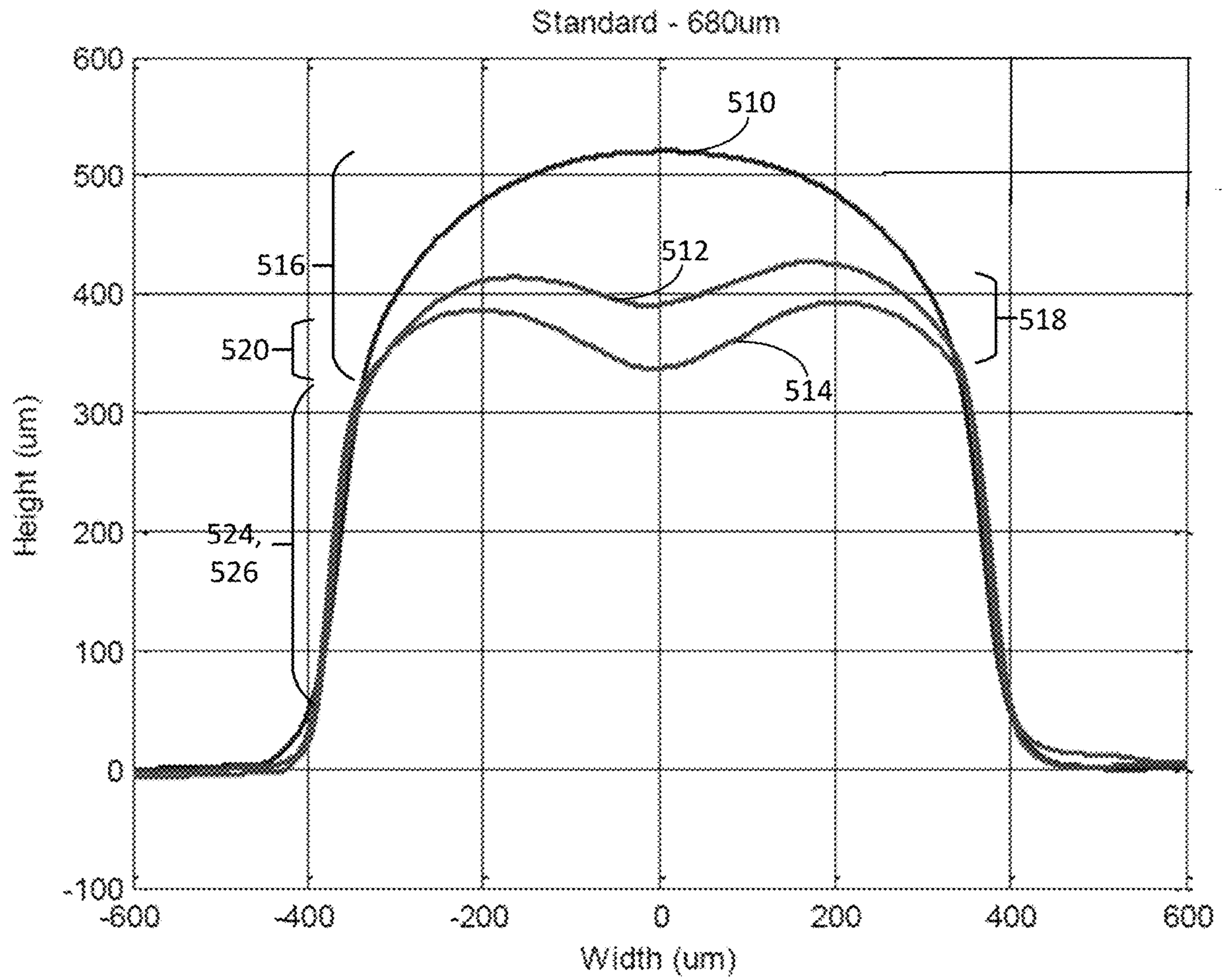


FIG. 9

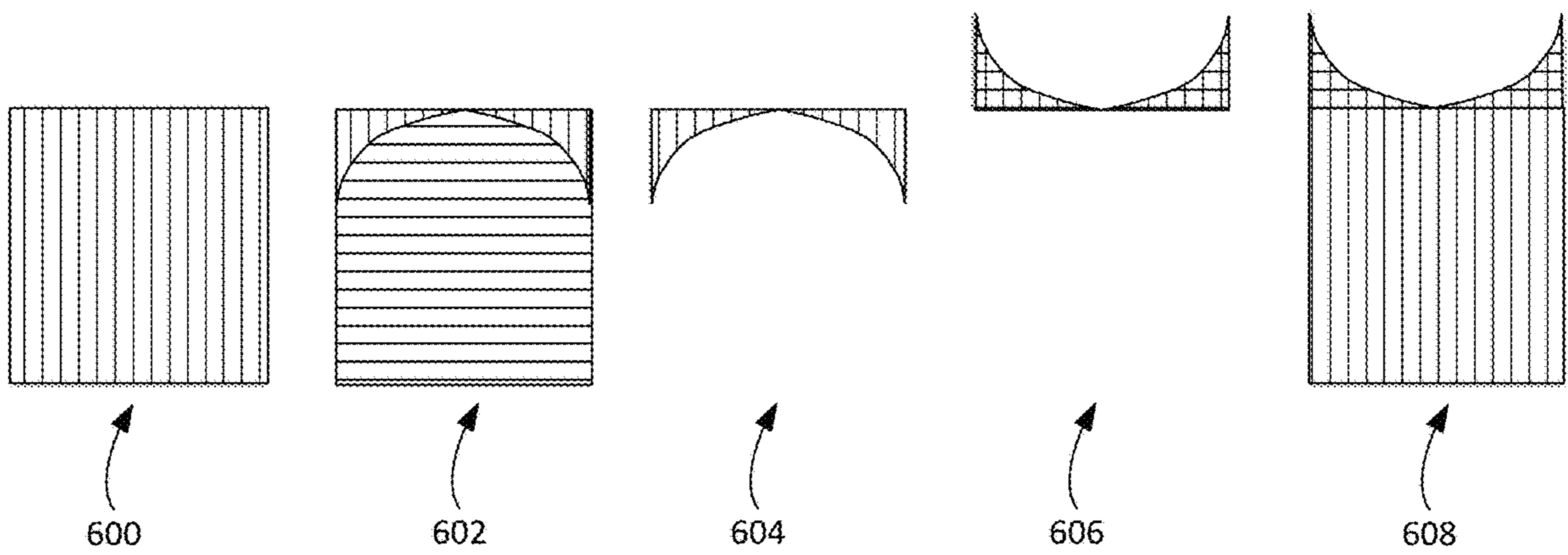


FIG. 10

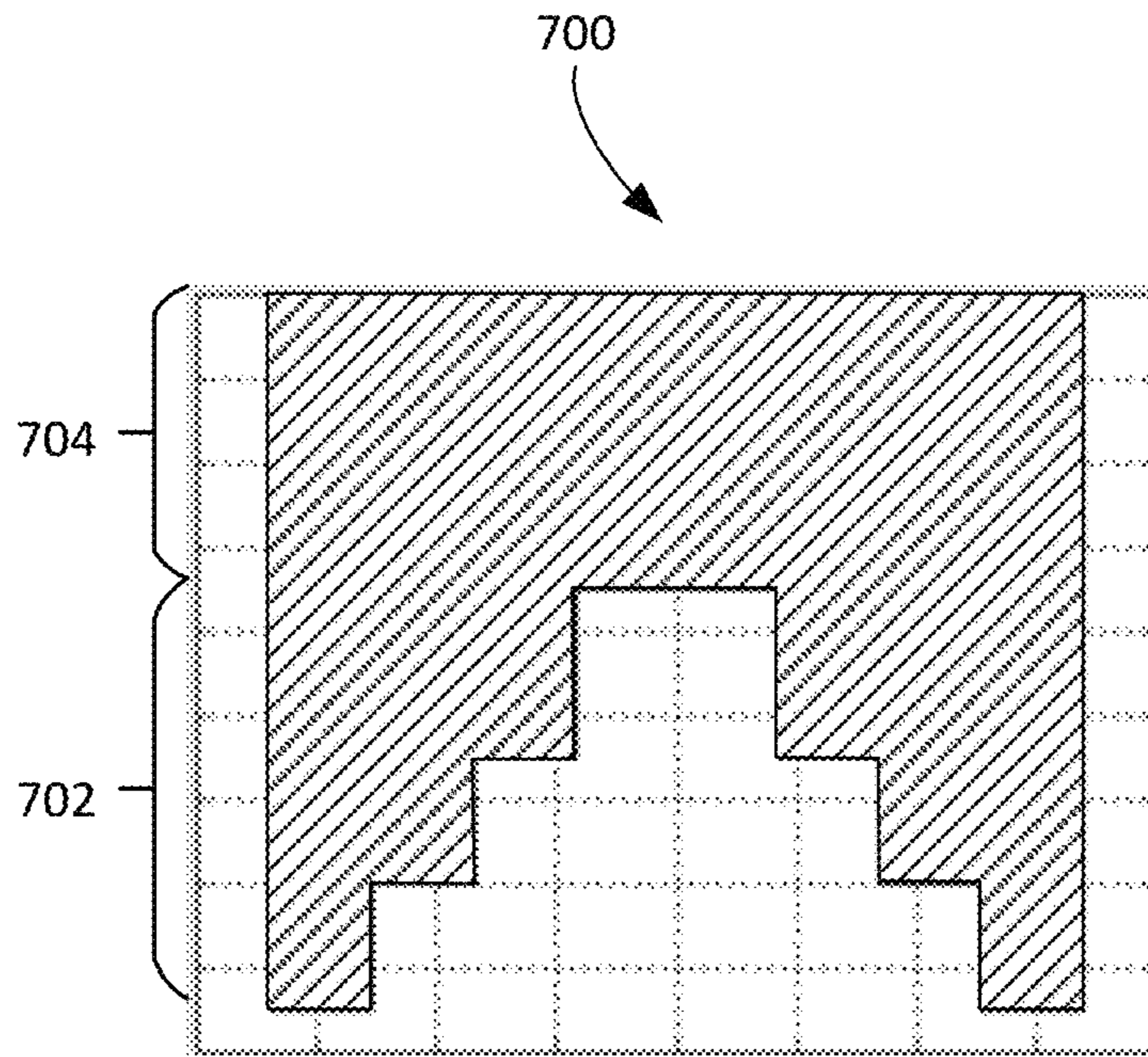


FIG. 11

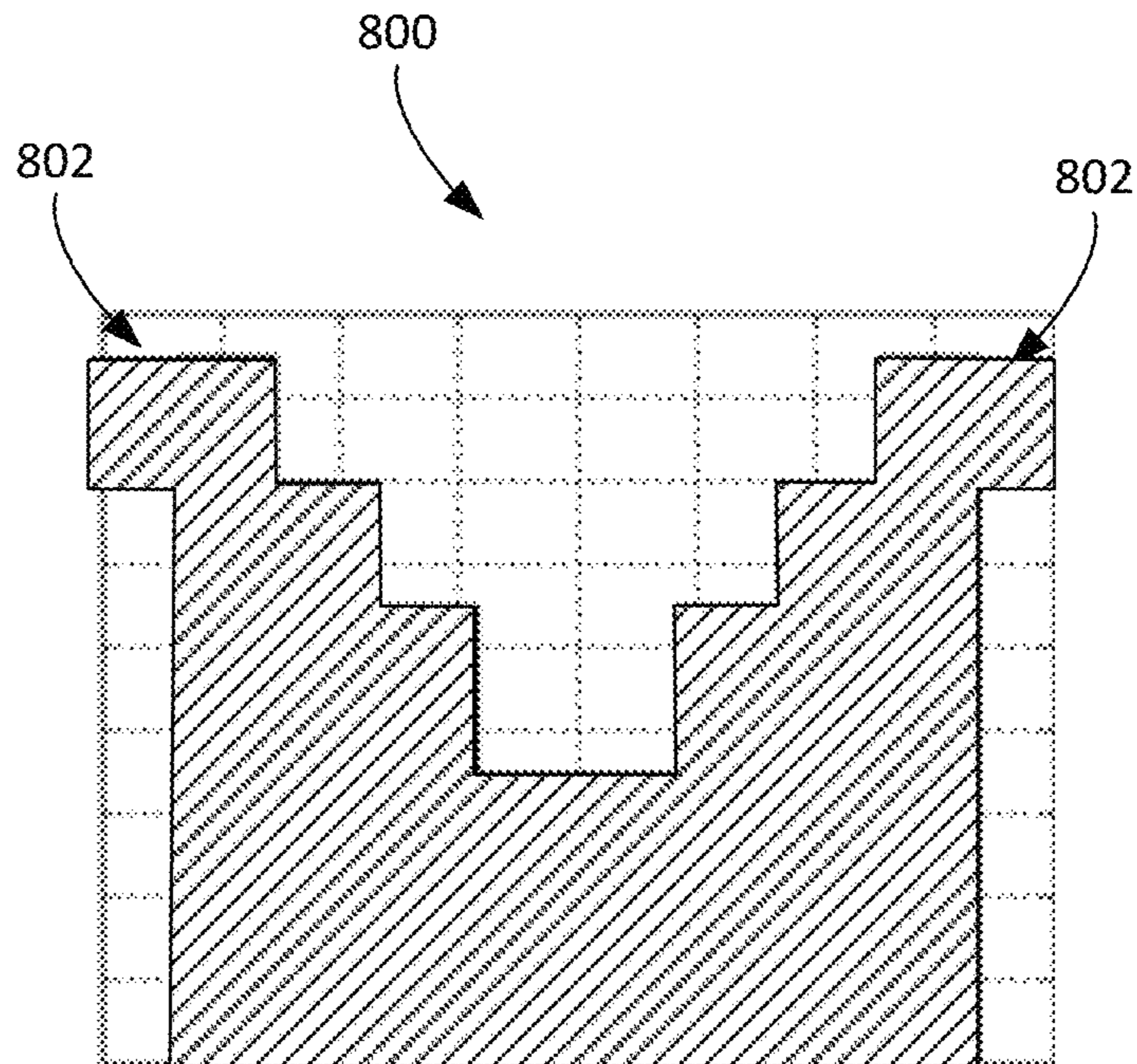


FIG. 12

CORRECTION OF FABRICATED SHAPES IN ADDITIVE MANUFACTURING

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/737,818, filed Jan. 8, 2020, which is a continuation of U.S. patent application Ser. No. 15/455,072, filed Mar. 9, 2017, which claims priority to U.S. Provisional Application Ser. No. 62/305,973, filed Mar. 9, 2016, the disclosures of which are incorporated by reference.

TECHNICAL FIELD

This specification relates to additive manufacturing.

BACKGROUND

An integrated circuit is typically formed on a substrate by the sequential deposition of conductive, semiconductive, or insulative layers on a silicon wafer. A variety of fabrication processes require planarization of a layer on the substrate. For certain applications, e.g., polishing of a metal layer to form vias, plugs, and lines in the trenches of a patterned layer, an overlying layer is planarized until the top surface of a patterned layer is exposed. In other applications, e.g., planarization of a dielectric layer for photolithography, an overlying layer is polished until a desired thickness remains over the underlying layer.

Chemical mechanical polishing (CMP) is one accepted method of planarization. This planarization method typically requires that the substrate be mounted on a carrier head. The exposed surface of the substrate is typically placed against a rotating polishing pad. The carrier head provides a controllable load on the substrate to push it against the polishing pad. A polishing liquid, such as slurry with abrasive particles, is typically supplied to the surface of the polishing pad.

One objective of a chemical mechanical polishing process is polishing uniformity. If different areas on the substrate are polished at different rates, then it is possible for some areas of the substrate to have too much material removed (“overpolishing”) or too little material removed (“underpolishing”). In addition to planarization, polishing pads can be used for finishing operations such as buffing.

Polishing pads are typically made by molding, casting or sintering polyurethane materials. In the case of molding, the polishing pads can be made one at a time, e.g., by injection molding. In the case of casting, the liquid precursor is cast and cured into a cake, which is subsequently sliced into individual pad pieces. These pad pieces can then be machined to a final thickness. Grooves can be machined into the polishing surface, or be formed as part of the injection molding process.

SUMMARY

In one aspect, a method of fabricating a polishing pad using an additive manufacturing system includes receiving data indicative of a desired shape of the polishing pad to be fabricated by droplet ejection. The desired shape defines a profile including a polishing surface and one or more grooves on the polishing pad. Data indicative of a modified pattern of dispensing feed material is generated to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and a plurality of layers

of the feed material are dispensed by droplet ejection in accordance to the modified pattern.

In another aspect, a method of fabricating an object using an additive manufacturing system includes receiving data indicative of a desired shape of the object to be fabricated by droplet ejection. The desired shape defines a profile including a top surface and one or more recesses. Data indicative of a modified pattern of dispensing feed material is generated to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and a plurality of layers of the feed material are dispensed by droplet ejection in accordance to the modified pattern.

In another aspect, a computer program product, tangibly embodied in a computer readable medium, includes instructions to cause a processor to receive data indicative of a desired shape of a polishing pad to be fabricated by droplet ejection in an additive manufacturing system. The desired shape defines a profile including a polishing surface and one or more grooves on the polishing pad. Data is generated indicative of a modified pattern of dispensing feed material to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and the additive manufacturing system is caused to dispense a plurality of layers of the feed material by droplet ejection in accordance to the modified pattern.

In another aspect, a computer program product, tangibly embodied in a computer readable medium, includes instructions to cause a processor to receive data indicative of a desired shape of an object to be fabricated by droplet ejection in an additive manufacturing system. The desired shape defines a profile including a top surface and one or more recesses. Data is generated indicative of a modified pattern of dispensing feed material to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and the additive manufacturing system is caused to dispense a plurality of layers of the feed material by droplet ejection in accordance to the modified pattern.

In another aspect, an additive manufacturing system includes a platform to hold a polishing pad being fabricated, a printhead to form a plurality of layer by ejecting droplets onto the platform or a previously deposited layer of the polishing pad, and a controller configured to receive data indicative of a desired shape of the polishing pad, the desired shape defining a profile including a polishing surface and one or more grooves on the polishing pad, generate data indicative of a modified pattern of dispensing feed material to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and cause the printhead to dispense a plurality of layers of the feed material by droplet ejection in accordance to the modified pattern.

In another aspect, an additive manufacturing system includes a platform to hold a polishing pad being fabricated, a printhead to form a plurality of layer by ejecting droplets onto the platform or a previously deposited layer of the polishing pad, and a controller configured to receive data indicative of a desired shape of the polishing pad, the desired shape defining a profile including a polishing surface and one or more grooves on the polishing pad, generate data indicative of a modified pattern of dispensing feed material to at least partially compensate for distortions of the profile caused by the additive manufacturing system, and cause the printhead to dispense a plurality of layers of the feed material by droplet ejection in accordance to the modified pattern.

Implementations may include one or more of the following features.

The one or more grooves on the polishing pad may be defined by a side wall substantially perpendicular to the plurality of layers. The distortions of the one or more grooves may include distortions of a perpendicularity of the side wall to the polishing surface.

The polishing surface may be substantially parallel to the plurality of layers. The modified pattern may be configured to at least partially compensate for distortions of the polishing surface of the polishing pad caused by the additive manufacturing system. The distortions of the polishing surface of the polishing pad may include distortions of a planarity of the polishing surface.

The data indicative of the desired shape of the polishing pad may include data indicative of a pattern of dispensing a plurality of layers of feed material, the data indicative of the pattern including data representing a planar top surface. The data indicative of the modified pattern may include data representing a concave top surface generated based on the data representing the planar top surface. The data representing the concave top surface may be generated to at least partially compensate for distortions of a planarity of a polishing surface of the polishing pad formed using the data indicative of the pattern.

Generating the data indicative of the modified pattern may include modifying data indicative of an original pattern to form the desired shape of the polishing pad. The data indicative of the original pattern may be modified based on a correction profile to the original pattern. The correction profile may include a portion extending beyond a width of the original pattern. The correction profile may be determined by identifying a difference between an original shape and the desired shape, the original shape being defined at least in part by the distortions. Modifying the data indicative of the original pattern may include modifying an amount of the feed material deposited per voxel.

The polishing surface may include a partition separating at least two grooves, and modifying the data indicative of the original pattern may include determining a first volume of material dispensed proximate an edge portion of the partition adjacent the groove, determining a second volume of material dispensed in a central portion of the partition, and modifying a distribution of volume of the feed material based on the first volume and the second volume such that the second volume is greater than the first volume.

The distortions of the profile caused by the additive manufacturing apparatus may include distortions caused by flow of ejected droplets on features being fabricated. The distortions of the profile may include distortions of a height of the one or more grooves. The desired shape of the polishing pad include a planar surface defining the polishing surface, and the modified pattern may include a nonplanar portion corresponding to the planar surface. The nonplanar portion may be configured to at least partially compensate for distortions of the polishing surface caused by the additive manufacturing system.

Advantages of the foregoing may include, but are not limited to, the following. The geometry of a polishing pad can be more precisely controlled, thereby improving polishing efficacy of the polishing pad. Furthermore, a correction profile can compensate for potential distortions by adjusting data that the additive manufacturing apparatus uses to form an article, e.g., a polishing pad, rather than removing material after the article has been initially formed. The amount of post-processing of the article after it is formed by the additive manufacturing apparatus can be

decreased. As a result, an amount of feed material waste can be reduced, and yield and throughput can be increased.

The details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other potential features, aspects, and advantages will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic side view of a polishing system.

FIG. 2 is a schematic side view of an additive manufacturing apparatus.

FIG. 3A is a top view of an example of a polishing pad.

FIG. 3B is a side view of the polishing pad of FIG. 3A.

FIG. 4 is a flowchart of a process to form an article.

FIG. 5 illustrates an example of an actual shape formed based on a desired shape.

FIG. 6 illustrates an actual shape formed based on modification of the desired shape of FIG. 5.

FIG. 7 illustrates another example of an actual shape formed based on a desired shape.

FIGS. 8A-8C are bitmap representations of patterns of feed material to be dispensed.

FIG. 9 illustrates resulting shapes formed using the bitmap representations of FIGS. 8A-8C.

FIG. 10 depicts a process of generating data indicative of a modified shape.

FIG. 11 is an example of a bitmap representation of a pattern of feed material to be dispensed in which an order of layers of feed material to be dispensed has been adjusted.

FIG. 12 is an example of a bitmap representation of a pattern of feed material to be dispensed in which a portion of the bitmap representation extends beyond an original width of a desired shape to be formed.

Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

An additive manufacturing apparatus can be used to form a polishing pad. The additive manufacturing apparatus can be provided with an initial pattern to dispense feed material. The initial pattern corresponds to a desired shape of the polishing pad to be formed. When the polishing pad is formed by the additive manufacturing apparatus using the initial pattern, an actual shape of the polishing pad may include distortions relative to the desired shape of the polishing pad. As described herein, the initial pattern provided to the additive manufacturing apparatus can be modified by a correction profile to generate a modified pattern to at least partially compensate for these distortions. The resulting shape formed using the modified pattern can thus more closely match the desired shape of the polishing pad.

Turning now to FIG. 1, a polishing system **100** includes a polishing pad **102** that can be used to polish one or more substrates **104**. A description of a suitable polishing apparatus can be found in U.S. Pat. No. 5,738,574, the entire disclosure of which is incorporated herein by reference. The polishing system **100** can include a rotatable platen **106** on which the polishing pad **102** is placed. During a polishing step, a polishing liquid **108**, e.g., abrasive slurry, can be supplied to a polishing surface **103** of polishing pad **102** by a slurry supply port or combined slurry/rinse arm **110**. The polishing liquid **108** can contain abrasive particles, a pH adjuster, or chemically active components.

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The substrate **104** is held against the polishing pad **102** by a carrier head **112**. The carrier head **112** is suspended from a support structure, such as a carousel, and is connected by a carrier drive shaft **114** to a carrier head rotation motor so that the carrier head can rotate about an axis **116**. The relative motion of the polishing pad **102** and the substrate **104** in the presence of the polishing liquid **108** results in polishing of the substrate **104**.

Referring to FIG. 2, in some examples, an additive manufacturing apparatus **120** that dispenses successive layers of feed material can be used to form the polishing pad **102**. Referring to FIGS. 1 and 2, the additive manufacturing apparatus **120** is operated to form at least a polishing layer **122** of the polishing pad **102**. In the manufacturing process, thin layers of feed material are progressively dispensed and cured. For example, droplets **124** of feed material, e.g., polishing pad precursor material, can be ejected from a nozzle **126** of a dispenser **128**, e.g., a droplet ejector printer, to form a layer **130** of the feed material. The dispenser **128** is similar to an inkjet printer, but uses the feed material for forming the polishing pad **102** rather than ink.

A controller **129** is operable to control dispensing operations of the dispenser **128** and, if applicable, control curing operations using an energy source **131** such as a lamp or a laser. The nozzle **126** is translated (shown by arrow A) across a support **134** to dispense feed material at any portion of a build area on the support **134**.

In some implementations, the energy source **131** trails the nozzle **126** as the nozzle **126** is translated across the support **134**, such that feed material dispensed through the nozzle **126** can be immediately cured. In some implementations, the energy source **131** leads the nozzle **126** as the nozzle **126** is translated across the support **134** in a first scanning direction while dispensing feed material. The energy source **131** can cure this dispensed feed material as the energy source **131** is scanned across the support **134**, e.g., in a second scanning direction opposite the first scanning direction, thereby providing the feed material additional time to reach a stable state before being exposed to radiation of the energy source **131**. In some implementations, the energy source **131** leads the nozzle **126** as the nozzle **126** is translated across the support **134** in a first scanning direction, and the energy source **131** is used to cure the dispensed feed material as the energy source is scanned in the first scanning direction. Thus, the previously dispensed layer of feed material can be cured almost immediately before another layer is dispensed through the nozzle **126**. In some implementations, there are multiple energy sources, with an energy source **131** trails the nozzle **126** and an energy source **131** that leads the nozzle **126**.

For a first layer **130a** deposited, the nozzle **126** can eject the feed material onto the support **134**. For subsequently deposited layers **130b**, the nozzle **126** can eject onto already solidified feed material **132**. After each layer **130** is solidified, a new layer is then deposited over the previously deposited layer until the full 3-dimensional polishing layer **122** is fabricated. Each layer is applied by the nozzle **126** in a pattern stored in a 3D drawing computer program that runs on a computer **60**. Each layer **130** is less than 50% of the total thickness of the polishing layer **122**, e.g., less than 10%, e.g., less than 5%, e.g., less than 1%.

The polishing layer **122** can be formed on a support **134**. In some examples, the support **134** includes a rigid base, or includes a flexible film, e.g., a layer of polytetrafluoroethylene (PTFE). If the support **134** includes a flexible film, then the support **134** forms a portion of the polishing pad **102**. For example, the support **134** can include a backing

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layer **136** (shown in FIG. 1) of the polishing pad **102** or a layer between the backing layer and the polishing layer **122**. If the support **134** includes the backing layer **136** of the polishing pad **102**, the support **134** is not removed from the polishing pad **102** after manufacturing of the polishing pad **102** is complete. Referring to FIG. 1, the polishing pad **102** is mounted to the polishing system **100** with the backing layer **136** (e.g., the support **134**) facing the rotatable platen **106**. Alternatively, if the support **134** does not include the backing layer **136** of the polishing pad **102**, the polishing layer **122** can be removed from the support **134** after manufacturing of the polishing pad **102** is complete.

Solidification of the layers **130** of feed material can be accomplished by polymerization. For example, the layer **130** of feed material can be a monomer, and the monomer can be polymerized in-situ by ultraviolet (UV) curing. The feed material can be cured effectively immediately upon deposition, or an entire layer **130** of pad precursor material can be deposited and then the entire layer **130** be cured simultaneously. Alternatively, the droplets **124** can be a polymer melt that solidifies upon cooling. In further implementations, the apparatus **120** creates the polishing layer **122** by spreading a layer of powder and ejecting droplets of a binder material onto the layer of powder. In this case, the powder could include additives, e.g., abrasive particles.

In some implementations, the backing layer **136** can also be fabricated by a 3D printing process. For example, the backing layer **136** and polishing layer **122** could be fabricated in an uninterrupted operation by the apparatus **120**. The backing layer **136** can be provided with a different hardness than the polishing layer **122** by using a different amount of curing, e.g., a different intensity of UV radiation, or by using a different material. In other implementations, the backing layer **136** is fabricated by a conventional process and then secured to the polishing layer **122**. For example, the polishing layer **122** can be secured to the backing layer **136** by a thin adhesive layer, e.g., as a pressure-sensitive adhesive.

In some implementations, referring to FIGS. 2, 3A, and 3B, when the polishing layer **122** is formed, the apparatus **120** can selectively dispense and/or selectively cure portions of the feed material to form grooves **138** in the polishing layer **122**. The grooves **138** can carry the polishing liquid **108** (shown in FIG. 1). The grooves **138** may be of nearly any pattern, such as concentric circles, straight lines, cross-hatching, spirals, and the like. Assuming grooves are present, partitions **140** between the grooves **138** define the polishing surface **103**. The polishing surface **103**, e.g., including the partitions **140** between the grooves **138**, can be about 25-90%, e.g., 70-90%, of the total horizontal surface area of the polishing pad **102**. Thus, the grooves **138** can occupy 10%-75%, e.g., 10-30%, of the total horizontal surface area of the polishing pad **102**. The partitions between the grooves **138** can have a lateral width of about 0.1 to 2.5 mm.

Referring to examples illustrated in FIGS. 3A and 3B, in some implementations, the grooves **138** include concentric circular grooves. These grooves **138** can be uniformly spaced with a pitch P . The pitch P is the radial distance between adjacent grooves **138**. The partitions **140** between the grooves **138** have a width W_p . Each groove **138** are defined by side walls **142** extending from a bottom surface **144** of the groove **138** and terminate in at the polishing surface **103**, e.g., at the partition **140**. Each groove **138** may have a depth D_g and a width W_g .

The side walls **142** can extend downwardly from and be generally perpendicular to the polishing surface **103**. In this

regard, the side walls are substantially perpendicular to the layers **130** of feed material dispensed on the support **134**. In addition, the partitions **140** extend substantially parallel to the layers **130** of feed material dispensed on the support **134**.

Each polishing cycle results in wear of polishing pad **102**, generally in the form of thinning of the polishing pad **102** as the polishing surface **103** is worn down. The width W_g of a groove with substantially perpendicular side walls **142** does not change as the polishing pad is worn. Thus, the generally perpendicular side walls **142** ensure that the polishing pad **102** has a substantially uniform surface area over its operating lifetime. As described herein, the manufacturing process to form the polishing pad **102** can include compensatory operations to prevent the polishing surface **103** from being nonplanar, e.g., to ensure planarity or flatness of the polishing surface **103**, and to fabricate the side walls **142** as perpendicular to the polishing surface **103**.

The grooves **138** can have a minimum width W_g of about 0.34 mm. Each groove **138** can have a width W_g between 0.34 mm and 2.71 mm, e.g., between about 0.38 mm and 1.02 mm. Specifically, the grooves **138** may have a width W_g of approximately 0.51 mm or 0.68 mm. The pitch P between the grooves **138** may be between about 0.68 and 6.10 mm, e.g., between about 2.29 mm and 5.40 mm. Specifically, the pitch may be approximately 2.03 or 3.05 mm. Each partition **140** between the grooves **138** may have a width W_p of at least 0.34 mm. The ratio of groove width W_g to partition width W_p may be selected to be between about 0.10 and 0.4. The ratio may be approximately 0.2 or 0.3.

In some implementations, if the polishing pad **102** includes the backing layer **136**, the grooves **138** can extend entirely through the polishing layer **122**. In some implementations, the grooves **138** can extend through about 20-80%, e.g., 40%, of the thickness of the polishing layer **122**. The depth D_g of the grooves **138** can be 0.25 to 1 mm. The polishing layer **122** can have a thickness T between about 1 mm and 3 mm. The thickness T should be selected so that the distance D_p between the bottom surface **144** of the groove **138** and the backing layer **136** is between about 0.5 mm and 4 mm. Specifically, the distance D_p may be about 1 or 2 mm.

Referring to FIG. 4, a manufacturing process **200** to form the polishing pad **102** is illustrated. For example, the additive manufacturing apparatus **120**, including the controller **129**, can perform the operations of the manufacturing process **200**.

At operation **202**, data indicative of a desired shape of the polishing pad **102** to be fabricated is received. Data indicative of shapes, including the data indicative of the desired shape, can be defined by a two-dimensional or three-dimensional bitmap. In some implementations, the shape data includes data representing a computer-aided design (CAD) model. For example, if the shape data corresponds to the data indicative of the desired shape, the CAD model is representative of the polishing pad **102** to be fabricated.

In some examples, referring to FIG. 5, the desired shape includes a desired feature **300**. Absent further manipulation of the data indicative of the desired shape, when the additive manufacturing apparatus **120** forms the desired shape, e.g., dispenses the feed material and cures or allows the feed material to cure to form the desired shape, an actual feature **310** may be formed based on the data indicative of the desired shape including the desired feature **300**. For example, to form the rectangular desired feature **300**, the dispenser **128** is controlled to dispense parallel layers **130** of feed material. For each layer, a selected portion of feed

material having a uniform width corresponding to a width of the rectangular desired feature **300** is cured.

During this dispensing and curing process, material properties and resolution of the additive manufacturing apparatus **120** can cause edges of the actual feature **310** to become undesirably rounded or beveled. In particular, if the layers **130** of feed material are dispensed in accordance to an original pattern determined based on the data indicative of the desired shape, the resulting shape includes rounding or beveling as depicted with respect to the actual feature **310**. As shown in FIG. 5, while a top surface **302** of the desired feature **300** is planar, a corresponding top surface **312** of the actual feature **310** is nonplanar. Due to a beveling effect on the top surface **312**, lateral edges **304a**, **304b** of the desired feature **300** have a greater length than actual lateral edges **314a**, **314b** of the actual feature formed by the additive manufacturing apparatus **120**. The desired feature **300** can correspond to the partitions **140** between the grooves **138** (shown in FIGS. 3A and 3B). In this regard, the rounding or beveling effect on the top surface **312** can cause the polishing surface **103** defined by the partitions **140** to become nonplanar. Without being limited to any particular theory, the liquid droplets of feed material ejected onto the previously deposited layer, e.g., the liquid pad precursor material, can spread and run down the sides of the feature **300**, e.g., due to wetting, resulting in the rounding.

To reduce the rounding or beveling effect, the data indicative of the desired shape can be modified. In this regard, referring back to FIG. 4, at operation **204**, data indicative of a modified pattern of dispensing feed material to compensate for polishing pad distortions is generated or received. The distortions include distortions of the polishing surface **103** of the polishing pad **102**. These distortions, in some cases, are caused by the additive manufacturing apparatus **120**, as described herein. The modified pattern differs from the original pattern of dispensing the feed material in that the modified pattern accounts for the distortions in the actual feature **310** relative to the desired feature. In this regard, in some implementations, the data indicative of the modified pattern is determined based on relative differences between the actual feature **310** and the desired feature **300**.

For example, as shown in FIG. 6, the data indicative of the modified shape includes data indicative of a modified feature **320**. Even though the top surface **302** of the desired feature **300** is planar, a top surface **322** of the modified feature **320** is nonplanar to compensate for the distortions of the top surface **312** of the actual feature **310** formed from the original pattern. The modified feature **320** is determined based on relative differences between the desired feature **300** and the actual feature **310**. The top surface **322** of the modified feature **320** is concave to compensate for the convexity of the top surface **312** of the actual feature **310**. In this regard, the data indicative of the modified shape is determined based on a combination of the data indicative of the desired shape and data indicative of the actual shape formed using the original pattern.

Referring back to FIG. 4, at operation **206**, layers **130** of the feed material are dispensed by droplet ejection in accordance to a modified pattern. A resulting actual feature **330** is formed based on data indicative of the modified pattern to dispense the feed material, the modified pattern being determined based on the data indicative of the modified shape.

When the dispenser **128** is controlled to dispense the layers **130** of feed material in accordance to the data indicative of the modified pattern, a size and shape of a selected portion of the layers **130** of feed material that is cured can vary through a height of the feature. This is in

contrast to the process to form the actual feature **310** in which the selected portion of cured feed material is consistent from layer to layer because the width of the desired feature **300** is consistent from layer to layer. The modified feature **320** includes a concave portion **326** having a width that varies from layer to layer. A modified pattern to dispense the feed material to form the concave portion **326** differs from the corresponding portion of the original pattern to form the top portion of the desired feature **300** in that the selected cured portions of the layers **130** of feed material for the modified pattern have varying widths and shapes. These varying widths and shapes compensate for the distortions present in the actual feature **310** such that the resulting actual feature **330** formed using the modified pattern has reduced convexity compared to the actual feature **310** formed using the original pattern. For example, a top surface **332** of the actual feature **330** has increased planarity and flatness compared to the top surface **312** of the actual feature **310**. By intentionally controlling where feed material is being dispensed and cured, this correction defined by the modified pattern can better match the shape of the resulting polishing pad **102** to the original desired shape for the polishing pad **102**.

For example, the controller **129** can receive a data object, e.g., a computer aided design (CAD)-compatible file that specifies the initial or intended bitmap. The data object can be stored on a non-transitory computer readable medium. The controller **129** can be programmed to generate a modified bitmap, based on the desired bitmap, that includes a feature to reduce rounding or beveling. Thus, when the polishing pad **102** is fabricated using the modified bitmap, it more closely matches the desired design.

FIG. 7 illustrates another example of a desired feature **400** and an actual feature **410** formed based on dispensing and curing patterns determined in accordance to the data indicative of the desired feature **400**. In this particular example, the desired feature **400** had a width of 680 μm and a height of 500 μm , although other dimensions are appropriate in an implemented process. As illustrated, the actual feature **410** had a non-planar top surface and slanted side walls.

The desired feature **400** is a constant width feature, e.g., the partition **140** separating the grooves **138** of the polishing pad **102**. A constant width of the partitions **140** can improve wafer-to-wafer polishing uniformity. Furthermore, the polishing efficacy of the polishing pad **102** can be dependent on planarity of the polishing surface **103**. Using the processes described herein, data indicative of a modified pattern can be generated so that the resulting actual feature formed using the modified pattern more closely matches the desired feature **400**. In particular, the modified pattern corresponds to the original pattern with an additional correction profile determined using processes described herein. The additional correction profile compensates for the distortions of the actual feature **410** formed using the original pattern.

The examples of FIGS. 8A-8C are representative of data indicative of shapes used by the additive manufacturing apparatus **120** to dispense and cure the feed material. In some implementations, the data indicative of the shapes described herein include bitmap representations of the shapes to be formed or the shapes formed. Each bit of the bitmap can correspond to a voxel of a feature of the polishing pad **102** to be formed. For example, FIG. 8A illustrates a bitmap representation **500** generated based on the desired feature **400**. FIG. 8B and FIG. 8C illustrate bitmap representations **502**, **504** generated to compensate for distortions of the actual feature **410**. The bitmap representations **502**, **504** are thus representative of modified

features generated based on the desired feature **400** and the actual feature **410**. The bitmap representations **502**, **504** include stepped portions **506**, **508** to approximate concavities of the modified features that compensate for the convexity of the actual feature **410**. The concavity approximated by the stepped portions **506** is less than the concavity approximated by the stepped portions **508**.

FIG. 9 illustrates resulting actual features **510**, **512**, **514** formed using modified patterns generally corresponding to the bitmap representations **500**, **502**, **504**, respectively. The actual features **510**, **512**, **514** include variable width portions **516**, **518**, **520**, respectively, with the variable width portion of the actual feature **510** having the greatest height. The variable width portion **518** has a height larger than the variable width portion **520**. Thus, a constant width can be more readily achieved through the bitmap representations **502**, **504** that include non-constant width patterns that compensate for distortions of the actual feature **510** formed using the bitmap representation **500**.

FIG. 10 illustrates an example process of determining a modified feature, and hence determining a modified pattern with which to dispense feed material to form a feature that better matches a desired feature. An actual shape is formed based on data representing a desired shape **600**, e.g., using the additive manufacturing apparatus **120** as described herein, and then data representing a measured shape **602** of the actual shape is determined. The data representing the measured shape **602** can be determined using, for example, a confocal laser microscope to measure the height profile of the actual shape. Data representing a difference **604** between the measured shape **602** and the desired shape **600** is then determined. The difference **604** can be indicative of the distortion of the measured shape **602** relative to the desired shape **600** and/or the distortion of the actual shape relative to the desired shape **600**. The difference **604** can correspond to the measured shape **602** being subtracted from the desired shape **600**. The data representing the difference **604** represents, for example, the portion of the measured shape **602** that does not match with the desired shape **600**.

Data representing an inverted difference **606** is determined based on the data representing the difference **604**. The data representing the inverted difference **606** is complementary to the difference **604**, thereby compensating for the distortion of the measured shape **602**. In some implementations, the inverted difference can be scaled anywhere from 1 to 3 times to form the data representing the inverted difference **606**. The inverted difference **606** corresponds to the correction profile used to modify the original desired shape **600**. In this regard, the data representing the inverted difference **606** is added to the data representing the desired shape **600** to form data representing a modified shape **608**. The data described in this example can correspond to bitmaps, as described herein.

The controller, e.g., the controller **129**, can be implemented in digital electronic circuitry, or in computer software, firmware, or hardware, or in combinations of them. The controller can include one or more computer program products, i.e., one or more computer programs tangibly embodied in an information carrier, e.g., in a non-transitory machine readable storage medium or in a propagated signal, for execution by, or to control the operation of, data processing apparatus, e.g., a programmable processor, a computer, or multiple processors or computers. A computer program (also known as a program, software, software application, or code) can be written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a

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standalone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program can be deployed to be executed on one computer or on multiple computers at one site or distributed across multiple sites and interconnected by a communication network.

The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed by, and apparatus can also be implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit).

The controller **129** and other computing devices part of systems described can include non-transitory computer readable medium to store a data object, e.g., a computer aided design (CAD)-compatible file that identifies the pattern in which the feed material should be formed for each layer. For example, the data object could be a STL-formatted file, a 3D Manufacturing Format (3MF) file, or an Additive Manufacturing File Format (AMF) file. For example, the controller could receive the data object from a remote computer. A processor in the controller **129**, e.g., as controlled by firmware or software, can interpret the data object received from the computer to generate the set of signals necessary to control the components of the additive manufacturing apparatus **120** to deposit and/or cure each layer in the desired pattern.

A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made.

In some implementations, referring to FIG. **12**, the correction profile includes portion extending beyond a width of the originally desired feature. A modified bitmap representation **800** includes a protruding portion **802** extending beyond a width of the bitmap representation **500** of the desired feature. The protruding portion **802** is dispensed, for example, with the uppermost layers of feed material. The layers of feed material underlying the uppermost layers of feed material may experience widening due to material roll off during dispensing. As a result, referring briefly to FIG. **7**, the underlying layers of feed material define a widened portion **402** that has a width larger than the width of the desired feature. The protruding portion **802** can correspond to feed material to be dispensed on top of the widened portion **402** to compensate for the variable width of the widened portion **402** and improve the consistency of the width of the feature at the widened portion **402**.

The approach shown in FIGS. **8B** and **8C** is to deposit one or more additional layers of feed material to compensate for the height of the feature being less than desired. For example, one or more additional layers of feed material can be deposited in regions where rounding or beveling occurs. However, alternatively or in addition, the amount of feed material deposited in a layer can compensate for the height feature being less than desired. For example, the size of droplets or the number of droplets ejected can be increased for voxels located in regions where the height of the feature is less than desired, e.g., where rounding or beveling occurs.

In some implementations, a distribution of volume of the feed material is modified depending on a location at which the droplets **124** are to be dispensed. A volume of the droplets **124** of feed material is varied during the dispensing operation. For example, referring back to FIG. **6**, the volume of the droplets **124** for forming edges **322a**, **322b** of the

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feature can be less than the volume of droplets **124** for forming the interior portion **322c** of the feature. The controller **129** determines the appropriate weight for forming the edges **322a**, **322b** and the weight for forming the interior portion **322c** based on the material properties of the feed material. The dispenser **128** can dispense less feed material to minimize roll off of the feed material. As the dispenser **128** moves to form the interior portion **322c** of the feature, the volume of droplets is increased. In some implementations, the volume of the droplets **124** define a gradient from the edges **322a**, **322b** to the center of the feature. Depending on the wetting effect of the feed material, this type of volume control can be used to modulate an amount of feed material cured when the energy source **131**, if present, is operated. For example, if the energy source **131** is scanned across the support **134** to cure different portions of the dispensed feed material, drop volume control can allow for less feed material to roll off for each pass of the energy source **131** while injecting more feed material at the edges **322a**, **322b** of the feature to reduce the beveling effect described herein.

In some implementations, multiple types of feed material are dispensed. The additive manufacturing apparatus **120** includes, for example, two or more dispensers, each dispenser dispensing a different type of feed material. In some cases, a single dispenser, e.g., the dispenser **128**, receives multiple types of feed material and dispenses a mixture of the multiple types of feed material. Because properties of a first type of feed material may vary from properties of a second type of feed material, the modification to the original pattern to dispense the first type of feed material may include a greater or smaller amount of scaling than the modification to the original pattern to dispense the second type of feed material. Alternatively, if droplet weight is controlled, the weights of the droplets of the first type of feed material can be controlled to be higher or lower than the weights of the droplets of the second type of feed material. In some cases, the size of the droplets of the first type of feed material can be controlled to be larger or smaller than the sizes of the droplets of the second type of feed material.

In some implementations, multiple types of feed material form different portions of the polishing pad **102**, for example, to form the polishing layer **122** and the backing layer **136**, or to form different portions of the polishing layer **122**, e.g., to provide a polishing layer with polishing properties that vary laterally across the polishing surface. The second type of feed material can include the first type of feed material with an additive that alters the properties of the second type of feed material relative to the first type of feed material. The additive includes, for example, a surfactant that can adjust properties of the uncured feed material, for example, zeta potential, hydrophilicity, etc.

Thickness of each layer of the layers of feed material and size of each of the voxels may vary from implementation to implementation. In some implementations, when dispensed on the support **134**, each voxel can have a width of, for example, 10 μm to 50 μm (e.g., 10 μm to 30 μm , 20 μm to 40 μm , 30 μm to 50 μm , approximately 20 μm , approximately 30 μm , or approximately 50 μm). Each layer can have a predetermined thickness. The thickness can be, for example, 1 to 80 μm , e.g., 2 to 40 μm (e.g., 2 μm to 4 μm , 5 μm to 7 μm , 10 μm to 20 μm , 25 μm to 40 μm).

Although the method and apparatus have been described in the context of fabrication of a polishing pad, the method and apparatus can be adapted for fabrication of other articles by additive manufacturing. In this case, rather than a polishing surface, there would simply be a top surface of the object being fabricated, and there would be recesses in the

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top surface. The modified pattern can at least partially compensate for distortions caused by the additive manufacturing system.

In addition, although the method and apparatus has been described in the context of fabrication by droplet ejection, the method apparatus can be adapted for fabrication by other additive manufacturing techniques, e.g., selective powder dispensing followed by sintering. Accordingly, other implementations are within the scope of the claims.

What is claimed is:

1. An additive manufacturing system, comprising:
 - a platform to hold an object being fabricated;
 - a printhead to form a plurality of successive layers of the object by ejecting droplets of precursor material onto the platform or a previously deposited and cured layer of the object;
 - a light source to cure the precursor material; and
 - a control system configured to
 - receive data indicative of a desired shape of the object, the desired shape defining a profile including a planar top surface and one or more recesses in the top surface, the one or more recesses separating features with top surfaces of the features providing the planar top surface,
 - based on data indicative of a desired shape of the object and data indicative of distortions of the profile caused by the additive manufacturing system, generate data indicative of a pattern of dispensing droplets of precursor material to at least partially compensate for the distortions of the profile, wherein the pattern includes a nonplanar portion corresponding to the planar top surface, the nonplanar portion configured to at least partially compensate for distortions of the planar top surface caused by droplets of the precursor material spreading down sides of the features,
 - cause the printhead to dispense a plurality of layers of the precursor material by droplet ejection in accordance to the pattern, and
 - cause the light source to cure the plurality of layers to form the object.
2. The system of claim 1, wherein the control system is configured to apply a correction profile to the desired shape to generate a modified shape, and to generate the data indicative of the pattern from the modified shape.
3. The system of claim 2, wherein the control system is configured to modify data indicative of the desired shape using the data indicative of the distortions to generate data indicative of a distorted shape of the object that would occur in absence of the pattern to at least partially compensate for the distortions of the profile.
4. The system of claim 3, wherein the control system is configured to determine the correction profile by calculating a difference between the distorted shape and the desired shape.
5. The system of claim 3, wherein the control system is configured to cause the printhead to add one or more additional layers of the precursor material to compensate for a height of a feature in the distorted shape being less than a desired height in the desired shape.
6. The system of claim 3, wherein the control system is configured to cause the printhead to increase an amount of the precursor material deposited per voxel to compensate for a height of a feature in the distorted shape being less than a desired height in the desired shape.

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7. The system of claim 1, wherein the control system is configured to detect from the data indicative of the desired shape a presence in the desired shape of a partition separating at least two grooves.

8. The system of claim 7, wherein the control system is configured to determine a first volume of material dispensed proximate an edge portion of the feature adjacent the recess, determine a second volume of material dispensed in a central portion of the feature, and modify a distribution of volume of the precursor material based on the first volume and the second volume such that the second volume is greater than the first volume.

9. A computer program product, tangibly embodied in a non-transitory computer readable medium, comprising instructions to cause a processor to:

receive data indicative of a desired shape of an object, the desired shape defining a profile including a planar top surface and one or more recesses in the top surface, the one or more recesses separating features with top surfaces of the features providing the planar top surface,

based on data indicative of a desired shape of the object and data indicative of distortions of the profile caused by an additive manufacturing system, generate data indicative of a pattern of dispensing droplets of precursor material to at least partially compensate for the distortions of the profile, wherein the pattern includes a nonplanar portion corresponding to the planar top surface, the nonplanar portion configured to at least partially compensate for distortions of the planar top surface caused by droplets of the precursor material spreading down sides of the features, and

cause a printhead of the additive manufacturing system to dispense a plurality of layers of the precursor material by droplet ejection in accordance to the pattern.

10. The computer program product of claim 9, comprising instructions to apply a correction profile to the desired shape to generate a modified shape, and to generate the data indicative of the pattern from the modified shape.

11. The computer program product of claim 10, comprising instructions to modify data indicative of the desired shape using the data indicative of the distortions to generate data indicative of a distorted shape of the object that would occur in absence of the pattern to at least partially compensate for the distortions of the profile.

12. The computer program product of claim 11, comprising instructions to determine the correction profile by calculating a difference between the distorted shape and the desired shape.

13. The computer program product of claim 11, comprising instructions to cause the printhead to add one or more additional layers of the precursor material to compensate for a height of a feature in the distorted shape being less than a desired height in the desired shape.

14. The computer program product of claim 11, comprising instructions to cause the printhead to increase an amount of the precursor material deposited per voxel to compensate for a height of a feature in the distorted shape being less than a desired height in the desired shape.

15. A method of fabricating an object using an additive manufacturing system, the method comprising:

receiving data indicative of a desired shape of the object, the desired shape defining a profile including a planar top surface and one or more recesses in the top surface, the one or more recesses separating features with top surfaces of the features providing the planar top surface,

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based on data indicative of a desired shape of the object and data indicative of distortions of the profile caused by the additive manufacturing system, generating data indicative of a pattern of dispensing droplets of precursor material to at least partially compensate for the distortions of the profile, wherein the pattern includes a nonplanar portion corresponding to the planar top surface, the nonplanar portion configured to at least partially compensate for distortions of the planar top surface caused by droplets of the precursor material spreading down sides of the features, and dispensing a plurality of layers of the precursor material by droplet ejection in accordance to the pattern, and curing the plurality of layers to form the object.

16. The method of claim **15**, comprising applying a correction profile to the desired shape to generate a modified shape, and generating the data indicative of the pattern from the modified shape.

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17. The method of claim **16**, comprising modifying data indicative of the desired shape using the data indicative of the distortions to generate data indicative of a distorted shape of the object that would occur in absence of the pattern to at least partially compensate for the distortions of the profile.

18. The method of claim **17**, comprising determining the correction profile by calculating a difference between the distorted shape and the desired shape.

19. The method of claim **17**, comprising adding one or more additional layers of the precursor material to compensate for a height of a feature in the distorted shape being less than a desired height in the desired shape.

20. The method of claim **17**, comprising increasing an amount of the precursor material deposited per voxel to compensate for a height of a feature in the distorted shape being less than a desired height in the desired shape.

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